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Enhanced denitrification in Downflow Hanging Sponge reactors for decentralised domestic wastewater treatment

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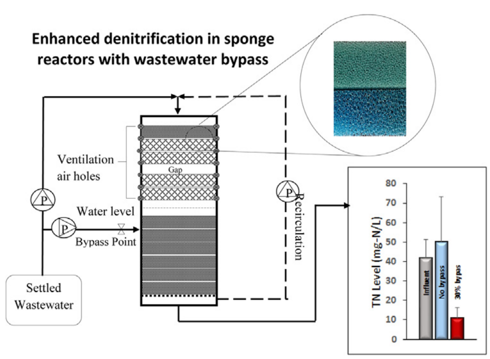
HIGHLIGHTS

- Past Downflow Hanging Sponge (DHS) designs have displayed limited denitrification.
- Poor denitrification occurs due to C-limitation and excess DO in lower sponges.
- A raw wastewater bypass was introduced to provide additional C and reduce DO.
- COD and TN removal rates of >84% and ~74% were achieved with a 30% v/v bypass.
- DHS reactors with bypass are suitable for decentralised treatment applications.

GRAPHICAL ABSTRACT



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ABSTRACT

Enhanced aerobic/anoxic Downflow Hanging Sponge (DHS) bioreactors were assessed for carbon (C) and total nitrogen (TN) removal for decentralised domestic wastewater treatment applications. The initial design included upper aerobic and lower anoxic sponge layers, and effluent recirculation, and achieved >80% COD_s and >90% NH_4-N removal. However, effluent TN was higher. It was concluded the anoxic layer was C-limited for denitrification, therefore an influent bypass was added to the anoxic layer to provide supplemental C. Differed bypass ratios were compared, including 0%, 10%, 20% and 30% (% of total influent), and effluent TN declined with increasing bypass; i.e., 50.1 ± 23.3 mg-N/L, 49.9 ± 27.8 mg-N/L, 31.9 ± 18.4 mg-N/L and 10.7 ± 5.8 mg-N/L, respectively, and all reactors removed >80% COD_s. This design has potential because it uses limited energy, tolerates variable flows, and simultaneously removes C and TN; all key for effective decentralised treatment applications.

1. Introduction

Billions of people worldwide do not have adequate domestic wastewater treatment, which leads to the spread of infectious disease and an estimated 2.1 million deaths every year (World Health Organisation (WHO), 2015). Despite some progress, the United Nations Millennium Development Goal (MDG) of halving the pro-

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portion of people without sustainable access to safe drinking water and basic sanitation has not been achieved for waste treatment, especially in Sub-Saharan Africa and South-East Asia (United Nations, 2015). Further, some emerging countries, such as China, have developed increasingly stringent laws on effluent discharges to the environment, particularly related to total nitrogen (TN) releases (Chan et al., 2009). As a consequence, domestic waste treatment is generally increasing, although often only in places where centralised sewage collection systems are feasible. This is largely because effective waste treatment in peri-urban and rural areas is still limited, especially waste treatment that removes TN (Jin et al., 2014; Lu, 2014), and few treatment options can remove both carbon (C) and TN that also are amenable to decentralised applications (Massoud et al., 2009; Naik and Stenstrom, 2016).

One possible option is Down-flow Hanging Sponge (DHS) bioreactors. This technology was originally visualised for decentralised use, and employs porous sponges and passive aeration to treat wastes (Agrawal et al., 1997; Tandukar et al., 2006; Tawfik et al., 2006). In principle, microbial consortia develop biofilms within the sponges (Mahmoud et al., 2011), metabolising C and secondary nutrients in the wastewater; transforming them into water, biomass and evolved gases (Uemura et al., 2010). DHS reactors have advantages over other treatment options, especially for low-income areas (Machdar et al., 2000; Tandukar et al., 2005), because they can be compact, are low maintenance, and operate with minimal energy input (Ahammad et al., 2013). Further, they utilise relatively short Hydraulic Retention Times (HRT) (Uemura et al., 2012) and have longer Sludge Residence Times (SRT), permitting the potential for higher Organic Loading Rates (OLR) and less sludge production compared with suspended-culture options (Tawfik et al., 2008).

Although previous DHS designs have shown effective C and ammonia (NH_3) removal (Onodera et al., 2014; Uemura et al., 2010), they display limited denitrification and often have elevated TN levels in effluents (Chuang et al., 2007). However, previous designs tend to entirely expose the sponge media to air to maximise passive aeration (Ikeda et al., 2013; Mahmoud et al., 2011; Uemura et al., 2010), which restricts denitrification because the reaction pathway requires anoxia. Limited denitrification diminishes the value of DHS reactors for decentralised use because of high TN releases, which is very pertinent to Chinese applications. Therefore, an alternate DHS reactor design was conceived that includes aerobic and anoxic modular sub-systems, which are driven by a raw wastewater bypass that provides extra C to the lower layers. The bypass is designed to encourage anoxia and alleviate C-limitation on denitrification (Isaacs and Henze, 1995; Shackle et al., 2000), increasing TN removal from the system.

2. Materials and methods

2.1. DHS reactor configurations

All DHS reactors tested included: 1) an upper sponge layer exposed to air, allowing passive aeration for nitrification; and 2) a lower sponge layer, partially submerged by effluent from the preceding aerobic layer, encouraging anoxic conditions for denitrification. However, detailed designs varied among experiments, employing different sponge densities (coarse vs fine; 20 vs 45 pores per inch, PPI, respectively) and recirculation ratios (0–100%), and the possible inclusion of a raw wastewater bypass (0–30% by volume).

Two sets of reactor experiments were performed, designated as Phase 1 and Phase 2. In Phase 1, quadruplicate bench-scale DHS reactors were operated using different combinations of sponge density (fine vs coarse); effluent recirculation ratios (see Fig. 1a); and steady and non-steady flow regimes. The Phase 1 reactors were physically identical 0.5 m tall × 140 mm diameter glass cylinders with working volumes of 3-L and inverted conical settlers at their bottoms. Reactors were designed in pairs based on combinations of different density sponges (R1 and R4 had coarse-coarse sponges and R2 and R3 had coarse-fine sponges; see Fig. 1a). R3 and R4 were operated with internal recirculation, whereas R1 and R2 had no recirculation to contrast the effect of waste recirculation on DHS reactor performance under differing flow conditions.

Phase 2 work used the same basic reactor design, except only the "best" sponge configuration and recirculation ratio from Phase 1 were employed. However, OLR was doubled, the reactors were made of PVC pipe (Crosslings, UK) instead of glass, and reactors were equipped with additional influent bypass lines to feed raw wastewater to the anoxic layer (Fig. 1b). The only difference among the four Phase 2 reactors was the percent of influent bypassed to the anoxic layer; either 0%, 10%, 20% and 30% of the total influent (by volume; designated R-S0, R-S10, R-S20 and R-S30, respectively). The reactors had side-holes every 30 mm (depth) on two sides that could be left open for added aeration, sealed with water-tight Suba-Seal (Sigma Aldrich, UK) closures, fitted with sampling ports (Point A and Point B), or used for bypass introduction. During these experiments, seals, taps and effluent tubing were positioned to maintain standing water depth of 240 mm in each column, fully submerging the lower sponge layer.

2.2. Inoculum and domestic wastewater

Settled domestic wastewater (post primary clarification; called "raw" here) was collected weekly from a municipal wastewater treatment plant (WWTP) in North East England (Tudhoe Mill, Northumbrian Water limited, UK) to serve as influent to the DHS reactors. Mean characteristics of the wastewater over the two Phases are summarised in Table 1. Samples were always collected at 9:00 AM on Tuesdays to minimise variations in reactor influent properties.

Reactors in both phases were seeded with nitrifying return active sludge (RAS) from the same WWTP (procedures are summarised in Supplementary Information; SI). However, Activated Sludge (AS) was used for reactor acclimation. AS and "raw" wastewater were collected in tandem during acclimation, and stored at 3–5 °C in sealed (raw wastewater) of unsealed (AS) containers prior to use. The raw wastewater was transferred every second day to an 18-L carboy retained in a fridge (4 °C) located near the reactors for short-term storage. Common waste was fed in parallel via influent pumps to all reactors, which were maintained at room temperature for all experiments (22–23 °C).

2.3. Polyurethane sponge media

Sponge cylinders 30-mm thick were cut to tightly fit inside the reactor columns. Each 30-mm cylinder had a working volume of 4.62×10^{-4} m^3. Phase 1 assessed the relative effect of using coarse versus fine density sponges for the upper and lower layers of the reactors (see Fig. 1a). Regardless of density, each sponge layer included three stacked sponge cylinders (90 mm total), making total sponge depths 180 mm. A similar, but slightly different sponge stacking/orientation was used in Phase 2. Specifically, the "aerobic" layer contained five stacked sponges, including four coarse-sponge cylinders (120 mm depth) topped by one fine sponge-cylinder. The lower sponge layer included six fine-sponge cylinders (180-mm depth). The fine-sponge layer at the reactor top was to screen out colloidal solids and better distribute raw feed within the aerobic sponges.

The aerated sponge layers were supported by PVC-coated wire mesh and hung suspended the top of the reactors with PVC coated

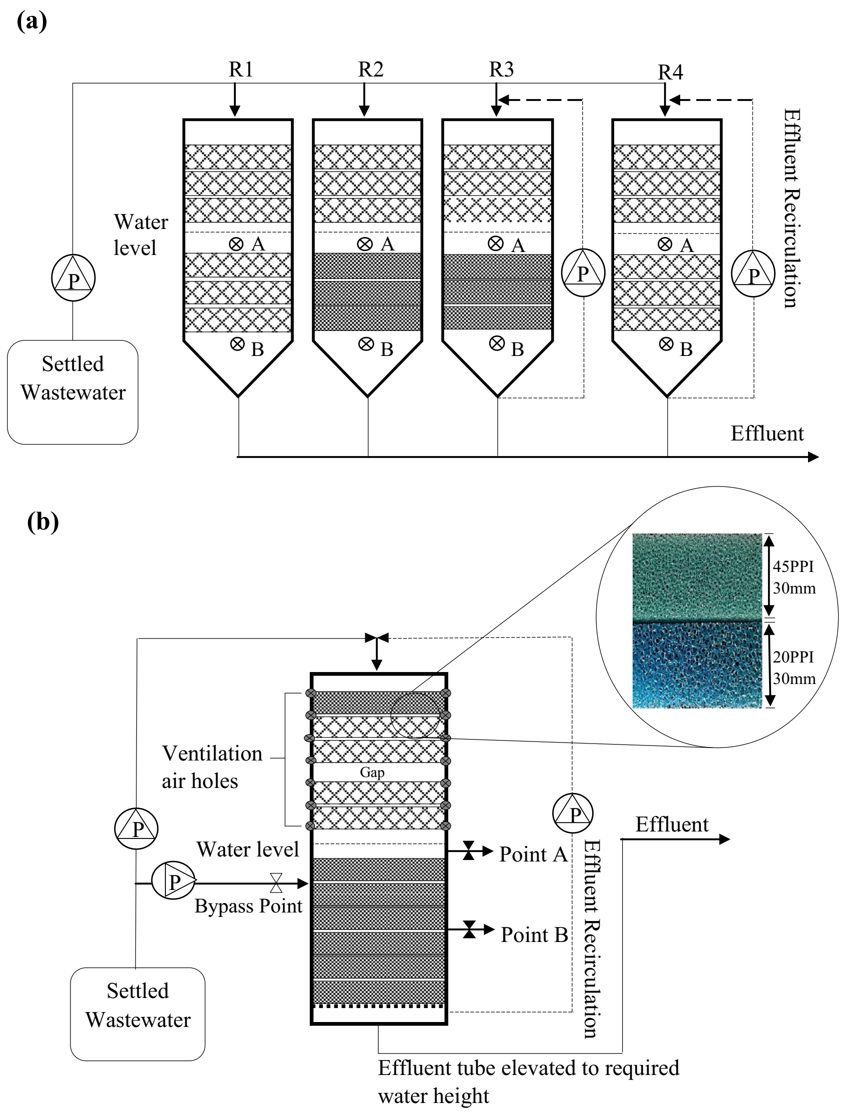

Fig. 1. DHS reactor configurations for (a) Phase 1 and (b) Phase 2. The core design includes an upper sponge layer suspended above the water level and then a lower submerged sponge layer. (a) Phase 1: Points A and B are sampling points below the upper and lower sponge layers, respectively, with access via side ports. Reactors had sponge layers had coarse (20 PPI) and-or fine (45 PPI) sponges as noted. R3 and R4 were operated with internal recycle, whereas R1 and R2 had no recycle and acted as control units. (b) Phase 2: Reactors R-S0 to R-S30 had four stacked 20 PPI sponge cylinders in the top and six 45 PPI sponge cylinders the bottom layer. Points A and B are sampling ports above and below the bypass entry point, which is as noted. The top layer had holes every 30 mm on two sides to allow aeration.

wire. The anoxic sponge layers were perched 30-mm from the base of the reactors on a perforated PVC plate support stand. Sponge core volumes were increased in Phase 2 reactors to increase sponge surface area because the OLR (kg COD/m^3-sponge/day) in Phase 2 was doubled (see below).

2.4. Reactor operating conditions

Raw wastewater was fed to the top of the reactors at controlled flowrates regulated by peristaltic pumps (Watson Marlow 520S, Watson and Marlow, UK). Typically, wastewater and recirculated effluent (where included) were blended above each reactor in a mixing tube and was passively dripped/dispersed onto a perforated plastic plate suspended 10-cm above the top sponge. The wastewater then “trickled” through the reactor column via gravity flow. A Watson Marlow 313U peristaltic pump with parallel pump heads was used to recirculate effluent from reactor bottoms (where employed) to the top of each reactor. PVC TYGON (F-4040-A, Saint Gobain, France) was used for all influent, recirculation, bypass and effluent lines.

After acclimation (days 0–21), Phase 1 was performed in three operating Stages as summarised in Table 1. During Stage 1 (S1; days 22–55), wastewater flow rate was 0.8 ml/min (OLR of ~0.2 kg COD/m^3-sponge/day; HRT = 1.2 days) and employed complete 100% recirculation in reactors R3 and R4 (i.e., 100% effluent return). In Stage 2 (S2; days 58–94), recirculation ratio was reduced to 50%, although OLR and influent flow rate was kept the same. However, in Stage 3 (S3; days 107–143), the flow regime was changed to three timed-intervals with 3.2 ml/min flow for two hours and then 0.0 ml/min flow for six hours (recycle was continued in R3 and R4). Daily OLR was identical to S1 and S2. The purpose of Stage 3 was to quantify reactor performance under non-steady flow conditions (with and without recirculation), typical of decentralised waste treatment applications.

Phase 2 reactors (R-S0, R-S10, R-S20 and R-S30) were fed wastewater at 2.14 ml/min with an OLR of 0.4 kg COD/m^3-sponge/day,

Table 1
Wastewater characteristics and operating conditions in both Phases.

Parameter	Phase 1			Phase 2
	Stage 1	Stage 2	Stage 3	
COD_s (mg/L)	172.6 (49.5)[a]	180.4 (27.6)	174 (36.2)	216.4 (40.7)
NH_3 (mg/L)	30.2 (4.7)	29.0 (5.8)	25.1 (4.4)	36.8 (8.7)
TN[b] (mg/L)	47.9 (11.7)	45.0 (7.5)	48.0 (5.0)	41.7 (9.6)
Flow regime	Continuous	Continuous	Intermittent[c]	Continuous
Feed flowrate (mL/min)	0.8	0.8	3.2	2.14
OLR[d]	0.2	0.2	0.2	0.4
HRT (Day)[e]	1.2	1.2	Variable	0.6
Recirculation rate (%) (when employed)	100	50	50	30
pH	7.4 (0.1)	7.6 (0.2)	7.7 (0.2)	7.0 (0.3)
Temperature	Room temperature (20–23 °C)			
Duration (Day)	33	37	48	47

Notes:
[a] Values in parenthesis represent standard deviations.
[b] TN is defined as the sum of TKN and anions-N ($NO^{-3} + NO^{-2}$).
[c] Wastewater was fed three time per day for two hours only at 3.2 mL/min. Reactors were not fed during intervening times, although recycle flow was continued throughout in units with recycle. The net daily waste volume per reactor was identical among Stages 1, 2 and 3.
[d] OLR is defined as kg COD/m^3-sponge/day and calculated using the total sponge volume.
[e] HRT calculated based on the top sponge volume because this is where primary COD and ammonia removal occurs. For hydraulic purposes, lower sponges act as a polishing unit.

which was double used in Phase 1 (HRT = 0.6 days). A 30% recirculation rate was used in Phase 2 in association with the higher OLR (Ikeda et al., 2013; Metcalf & Eddy, 2003). R-S0 to R-S30 had actual bypass percentages of 0.0, 9.1, 18.0 and 31.4%, respectively, and the bypass feed entered the anoxic layer at the Bypass Point (see Fig. 1b).

2.5. Chemical analysis

Monitoring of reactor operations included soluble Chemical Oxygen Demand (COD_s), Total Kjeldahl Nitrogen (TKN), ammonia-nitrogen (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N). All Phase 1 analyses were conducted in accordance to the Standard Methods for Examinations of Water and Wastewater (APHA, 1998). Analysis methods in Phase 2 were the same as Phase 1, except colorimetric test kits (Merck, Germany) analogous to the APHA methods were used for CODs (Spectroquant 25–1500 mg/L cell test) and NH_4-N (Spectroquant 2–150 mg/L NH_4-N).

Anion analysis was performed using Ion Chromatography (IC) on an ICS-1000 system (Dionex, USA) fitted with an AS40 auto sampler (Thermo scientific, UK). The IC was equipped with a conductivity detector and an anion column for separations (Ionpac AS14A, 4 × 250 mm analytical, Dionex, USA). Samples were filtered using 0.2 μm PES syringe filters (VWR, UK) prior to analysis (in duplicate) alongside pre-prepared standards for TKN, NH_4-N and anions (Sigma Aldrich, UK). Therefore, soluble values are reported for all parameters. Total nitrogen (TN) is defined as the sum of TKN and nitrogenous anions (NO_3–N and NO_2–N). The pH and DO concentrations were quantified using 3310 (Bibby Scientific Ltd., UK) and FirestingO2 sensor (Pyroscience, Germany), respectively. Regular instrument calibration was performed according to manufacturer's instructions.

2.6. Statistical analysis

All statistical analysis was performed using SPSS (V19.0, IBM, USA). Experimental outliers were first removed from further statistical analysis according to the interquartile range (IQR) method (i.e., if >1.5 times the IQR; Montgomery and Runger, 2007). One-way ANOVA was used to determine the difference between parameter means, whereas Two-way ANOVA was used to define the main "effect variable(s)" to reduce possible errors due to multiple-group or repeated comparisons. Non-parametric statistical methods were employed when data were non-Normal, typically using the Mann-Whitney (MW) test. Statistical significance always was defined by 95% confidence limits (i.e., $p < 0.05$).

3. Results and discussion

3.1. Improving DHS reactors for decentralised wastewater treatment

DHS systems are operationally simple, require minimal maintenance after acclimation, can be modified according to local needs/resources, and are not heavily energy demanding (Fleifle et al., 2013). While DHS technologies have shown promise for decentralised wastewater treatment applications in emerging countries, such systems always have had difficulty reducing TN in the wastes due to inadequate denitrification. Therefore, alternate DHS designs that sustain denitrification, especially for waste treatment at smaller scales (i.e., amenable to decentralised treatment), are vital to DHS technology implementation in the emerging world.

Various approaches for promoting denitrification are possible, but new designs must retain positive traits of previous DHS reactors, such as simplicity and low energy use. Within this context, it was speculated denitrification could be promoted by submerging the bottom sponge layers with wastewater, promoting anoxia due to microbial oxygen consumption (Ahammad et al., 2013). In theory, denitrifying species would be enriched and convert nitrate released from the upper sponge layers to nitrogen gas (Fleifle et al., 2013). Although the concept has potential, design options and operational performance must be assessed, including "suitable" sponge arrangements and densities; the value of effluent recirculation; and defining appropriate nutritional needs in lower sponge layers that promote denitrification at feasible reactor OLRs. These factors were examined and optimised through two Phases of staged experiments, which are reported herein.

3.2. Phase 1: No wastewater bypass employed

3.2.1. Effect of sponge pore sizes and recirculation rates

Phase 1 reactor performance data for COD_s, ammonia and TN are summarised in Fig. 2 (over time) and Table 2 (means). The first

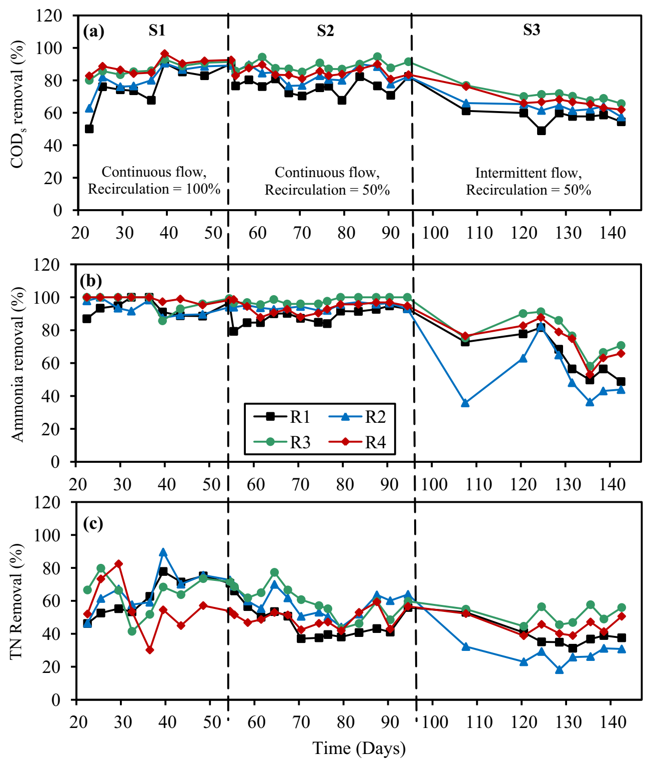

Fig. 2. Removal efficiencies for (a) COD (b) Ammonia and (c) TN for the four reactors during the three stages of Phase 1. The reactor stages included: Stage 1 = continuous flow, 100% effluent recycle; Stage 2 = continuous flow, 50% effluent recycle; Stage 3 = intermittent flow, 2/6 h on/off cycle, 50% effluent recycle (where applicable). Reactors with recycle consistently performed better than reactors without recycle. This was most apparent during intermittent flow, which is typical of flow conditions in small, decentralized wastewater treatment systems.

two stages (S1 and S2) assessed the influence of effluent recirculation ratio (0%, 50% and 100%) and sponge-density configuration (fine-coarse and coarse-coarse) on reactor performance. In summary, the four reactors removed COD_s (60–90%) and TN (40–70%) at differing degrees. COD_s removal rates were significantly higher in reactors with effluent recirculation relative to reactors without recirculation ($p < 0.01$; i.e. R1 vs R4 and R2 vs R3). Further, reactors with fine-density bottom-sponges had significantly higher COD_s removal levels, especially during S2 (two-way ANOVA; $p < 0.01$), possibly due to reduced passive aeration into the fine bottom-sponges. As such, COD_s removal rates were highest in the reactors with mixed coarse-fine sponges and effluent recirculation (i.e., R3).

In contrast, neither recirculation nor different density sponges significantly altered TN removal rates during S1 and S2 (Fig. 2c). Ammonia removal efficiency averaged 94.4% across reactors in S1 and S2 (Table 2) with no significant differences relative to sponge type or recirculation regime (MW test, $p > 0.05$). However, TN removal levels were lower, typically ~60% with mixed sponge reactors (R2 and R3) and ~50% in coarse-coarse sponge units (R1 and R4). Clearly, efficient nitrification was occurring in top sponges in all reactors, even without recirculation, whereas only partial denitrification was occurring in the lower sponges, despite being submerged.

To determine why this was the case, DO measurements were made at points A and B (see Fig. 1a), and DO was found to be ~4.0 mg/L at the top of the bottom sponges and DO was detectable in reactor effluents (see Table S1; 0.2–1.3 mg/L). DO data suggest air was diffusing into the lower sponges, preventing anoxia from developing and inhibiting denitrification, which requires DO < 0.2 mg/L (U.S. Environmental Protection Agency (USEPA), 2010; Wrage et al., 2001). Further, the top sponge layers effectively reduced COD_s levels. It was, therefore, concluded that lower sponges were oxygen-inhibited and C-limited for denitrification, despite recirculation. Therefore, modifications were needed to the reactors to promote denitrification.

3.2.2. Effects of non-steady flow conditions on C-removal and nitrification

Although TN removals were not as hoped in S1 and S2, it was desired to assess how C-removal rates and nitrification in the reactors might respond to variable flow conditions, which are typical of small-scale, decentralised waste treatment applications. Therefore, reactor operations were continued (i.e., S3), but flow conditions were changed to a two hours on, six hours off flow regime. Daily OLR was not changed. The goal was to assess how effluent recirculation influenced reactor performance, especially nitrification, when influent feed and reactor flow non-steady and intermittent.

Switching to an intermittent feed substantially reduced COD_s, ammonia and TN removal rates (Table 2), even though wastewater characteristics were similar (Table 1). However, reductions in removal rates were most profound in reactors without recirculation. In particular, NH_4 removal was consequentially affected (i.e., nitrification); dropping to ~50% without recirculation and ~70% with recirculation, which is significantly poorer performance than in S1 and S2 (MW test; $p < 0.05$). Fig. 2b and c show the decline in NH_4 removal level roughly paralleled reductions in TN removal, especially without recirculation (i.e., 60%–30% and 60%–40%, respectively; MW, $p < 0.01$). To elucidate lower TN and COD_s removal rates observed in S3, DO again was measured in the reactors. Upper sponge DO levels were generally lower in S3 reactors, especially without recirculation (Table S1), possibly explaining reduced nitrification rates. As a result, effluent recirculation was concluded to be essential in the design to reduce negative impacts of non-steady flow conditions typical of smaller scale, decentralised applications.

3.3. Phase 2: Wastewater bypass in promote denitrification

3.3.1. Enhancing TN removal using an influent bypass

Phase 1 work showed that DHS reactors with a coarse-fine sponge configuration and effluent recirculation had highest COD_s and NH_4 removal rates, and were least affected by non-steady flow conditions. However, none of the Phase 1 reactors achieved the EU guideline levels of 10 mg-N/L (Council of the European Union, 1991) nor the Chinese Wastewater Standard GB18918-2002 of 15 mg-N/L (Ministry of Environmental Protection (MEP), 2002). Clearly, consequential denitrification was not occurring in the lower sponge layer, which is especially concerning given the reactors were being operated at relatively low OLRs (0.2 kg COD/m^3-sponge/day). DO and COD_s data implied lower sponge layers were not anoxic, partially because the top sponges were removing COD_s so well that the lower sponge layer was deficient in C relative to denitrification. Therefore, a raw wastewater bypass was added to the reactor design (see Fig. 1b) and four different bypass percentages were compared in parallel reactors over 120 days.

Reactor performance in Phase 2 is summarised in Table 3 and Fig. 3. Although OLR was doubled in Phase 2 (to 0.4 kg COD/m^3-sponge/day) and only 30% recirculation was employed, COD_s and NH_4 removal rates were always >84% and >81%, respectively. However, TN removal rate progressively improved as percentage bypass was increased with the R-S30 reactor (30% bypass) having a mean effluent TN of 10.7 ± 5.8 mg/L (removal rate = 74.3%). Presumptively, the raw wastewater bypass was simultaneously reducing DO and providing the needed degradable C for denitrification. This is corroborated by only 1.9 ± 3.0 mg NO_3-N/L being present in R-S30 effluent compared with 46.0 ± 22.6 mg NO_3-N/L in the reactor

Table 2
Summary of reactor performance during Phase 1 operations.

Parameter (mg/L)	Influent	R1[b]		R2		R3		R4	
		Effluent	R%	Effluent	R%	Effluent	R%	Effluent	R%
Stage 1[a]									
COD_s	172.6 (49.5)[c]	46.0 (19.5)	72.0	38.6 (15.8)	76.5	26.8 (11.0)	84.3	22.6 (9.2)	86.6
TN	47.9 (11.7)	22.3 (8.6)	54.6	16.4 (7.9)	66.6	17.5 (4.0)	61.9	21.0 (2.3)	53.6
NH_4-N	30.2 (4.7)	2.3 (1.1)	91.9	2.0 (1.4)	93.0	1.0 (1.6)	96.6	0.4 (0.5)	98.6
NO_2-N	BDL[d]	2.5 (1.2)	–	1.5 (0.9)	–	0.6 (0.4)	–	1.1 (0.7)	–
NO_3-N	BDL	5.6 (2.9)	–	5.3 (1.4)	–	7.1 (3.2)	–	9.9 (4.5)	–
Stage 2									
COD_s	180.4 (27.6)	43.3 (11.9)	75.7	33.1 (12.0)	81.4	23.4 (7.7)	86.9	31.5 (8.9)	82.3
TN	45.0 (7.5)	20.1 (6.7)	56.3	16.6 (4.5)	63.4	16.6 (3.6)	62.8	21.9 (4.9)	51.5
NH_4-N	29.0 (5.7)	3.3 (1.3)	88.2	2.0 (1.2)	93.1	0.7 (0.5)	97.5	2.5 (1.4)	91.2
NO_2-N	BDL	0.6 (0.1)	–	0.5 (0)	–	0.3 (0.1)	–	0.8 (0.1)	–
NO_3-N	BDL	7.7 (3.6)	–	5.7 (1.1)	–	5.0 (1.4)	–	9.1 (1.5)	–
Stage 3									
COD_s	178.4 (37.1)	79.3 (19.7)	54.5	66.9 (13.6)	61.3	52.9 (11.8)	69.3	59.9 (15.0)	65.2
TN	48.8 (5.2)	30.7 (4.6)	36.8	36.5 (3.7)	24.9	24.4 (3.1)	49.7	27.9 (3.6)	42.4
NH_4-N	25.2 (4.4)	9.6 (3.8)	59.8	12.7 (4.8)	46.2	6.3 (3.5)	72.6	7.4 (3.5)	68.5
NO_2-N	BDL	0.3 (0.7)	–	0.8 (1.5)	–	1.0 (1.5)	–	0.4 (0.5)	–
NO_3-N	BDL	BDL	–	BDL	–	0.1 (0.2)	–	BDL	–

Notes:
[a] Stage 1 = continuous flow, 100% effluent recirculation in R3 and R4, 0% recirculation in R1 and R2; Stage 2 = continuous flow, 50% recirculation in R3 and R4, 0% in R1 and R2; Stage 3 = intermittent flow, 2/6 h on/off cycle, 50% recirculation in R3 and R4, 0% in R1 and R2.
[b] See Fig. 1(a). R1 = coarse-coarse sponges, no recirculation; R2 = course-fine sponges, no recirculation; R3 = coarse-fine sponges, recirculation; R4 = coarse-coarse sponges, recirculation.
[c] Values in parenthesis represent standard deviations.
[d] BDL = Below detection limit.

Table 3
Summary of reactor performance during Phase 2 operations.

Parameter (mg/L)	Influent	R-S0[a]		R-S10		R-S20		R-S30	
		Effluent	R%	Effluent	R%	Effluent	R%	Effluent	R%
COD_s	216.4 (40.7)[b]	29.8 (19.3)	86.2	24.3 (11.1)	88.8	30.3 (16.6)	86.0	34.1 (14.1)	84.2
TN	41.7 (9.6)	50.1 (23.3)	−20.1	49.9 (27.8)	−19.7	31.9 (18.4)	23.5	10.7 (5.8)	74.3
NH_4-N	36.8 (8.7)	2.2 (3.5)	94.0	0.4 (0.6)	98.9	0.9 (1.2)	97.6	6.9 (4.7)	81.3
NO_2-N	BDL[c]	2 (2.5)	–	0.7 (1.1)	–	0.9 (1.4)	–	0.1 (0.2)	–
NO_3-N	BDL	46.0 (22.6)	–	48.8 (28.4)	–	28.4 (19.1)	–	1.9 (3.0)	–

Notes:
[a] See Fig. 1(b) for details. R-S0 = 0.0 wastewater bypass; R-S10 = 10% wastewater bypass; R-S20 = 20% wastewater bypass; R-S30 = 30% wastewater bypass.
[b] Values in parenthesis represent standard deviations.
[c] BDL = Below detection limit.

without bypass R-S0. Conversely, NH_4 levels in R-S30 effluent were higher (i.e., 6.9 ± 4.7 mg NH_4-N/L) than the other reactors, suggesting ammonia in bypassed raw wastewater was not being fully treated in the lower sponge due to anoxic conditions. Interestingly, the lowest effluent ammonia levels were seen in R-S10 and R-S20 (0.4 ± 0.6 and 0.9 ± 1.2 mg-N/L, respectively), which is higher than R-S0 without a bypass (2.2 ± 3.5 mg NH_4-N/L). This implies the ammonia loading rate to R-S0 was apparently in slight excess, and 10–20% influent waste bypass was needed to improve ammonia treatment efficiency in the units.

Overall, data imply bypassing wastewater is an effective method of enhancing denitrification in DHS reactors, although

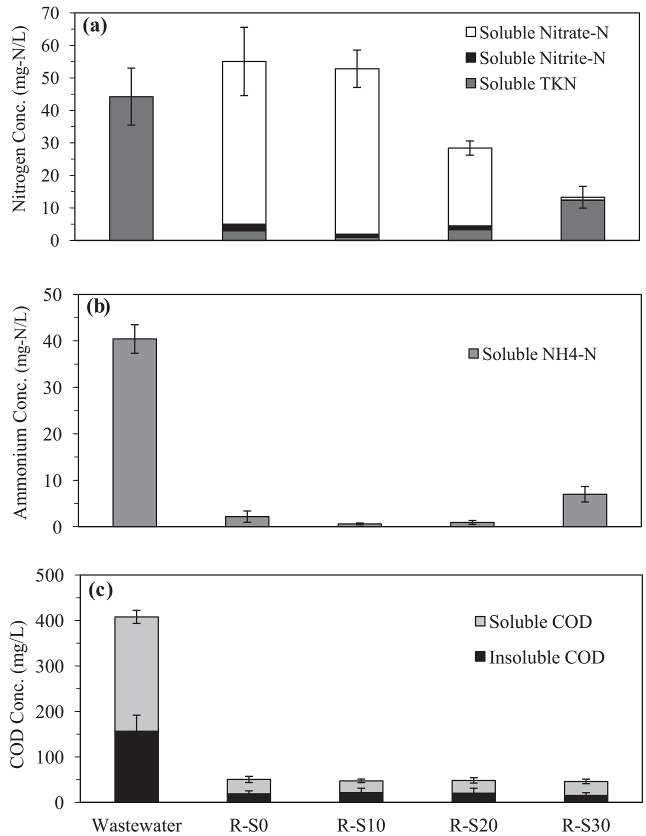

Fig. 3. DHS Reactor mean performance as a function of percent wastewater bypass (Phase 2). (a) TN concentrations subdivided among soluble TKN, nitrite and nitrate; (b) Ammonia-N; and (c) COD constituents in the settled wastewater and effluents of reactors (n = 8 per reactor) over 47 days of operation after acclimation. Error bars reflect standard error around the means.

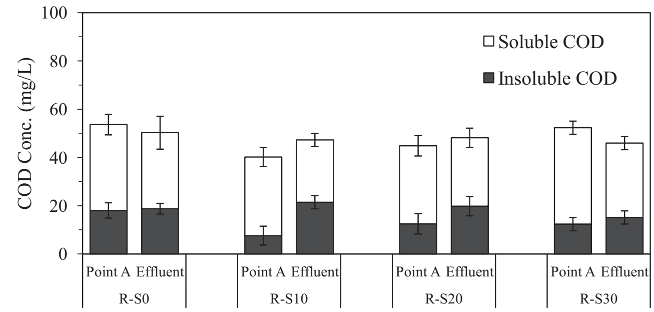

Fig. 4. COD levels (insoluble and soluble components) in wastewater after aerobic treatment (before entering the secondary anoxic layer) and the final effluent. Error bars denote standard error for total COD (n = 8).

the preferred bypass percentage in any particular application may differ based on various factors. For example, bypass intrinsically means some raw wastewater will not pass through the upper aerobic layer, therefore treatment mechanisms requiring aeration might be impaired, such as nitrification. The importance of this limitation will depend on temperature, OLR, HRT and other operating factors, but as reactor design is refined, experience will define optimal bypass percentages in due course.

Regardless, wastewater bypass clearly promotes denitrification, almost certainly by increasing available C for denitrifying bacteria in the lower sponge. This is supported by data presented in Figs. 3c and 4, which summarises total COD levels in the intermediate layer and reactor effluent (Total COD = COD_s plus insoluble COD). No major difference in effluent COD levels is observed despite untreated wastewater being bypassed to the lower sponge, suggesting bypassed COD is being removed in the lower sponge in conjunction with reductions in TN (see RS-30, Table 3).

3.3.2. Ammonia, nitrate and nitrate levels versus bypass percentage

Bypassing raw wastewater clearly improves overall denitrification and reduces effluent TN levels (i.e., TN = 50.1 ± 23.3, 49.9 ± 27.8, 31.9 ± 18.4, and 10.7 ± 5.8 mg-N/L for 0, 10, 20 and 30% bypass, respectively), but the percent of bypass significantly changes the composition of effluent N constituents. At 0 and 10% bypass, higher effluent NO_3 and lower NH_3 levels are observed (Table 3), suggesting efficient nitrification is occurring in the top sponge, although insufficient available C is provided to the bottom sponge to support denitrification. In contrast, at 30% bypass one sees low effluent NO_s levels and higher NH_3 levels, implying efficient denitrification, but increased levels of untreated ammonia leaving the reactor.

In reality, an "optimal" bypass rate was not achieved here, although data suggest a bypass rate between 20 and 30% might be suitable for this wastewater under these operating conditions. Regardless, the basic principle is confirmed; i.e., if one bypasses a small portion of the raw influent to the lower sponge layer, DHS reactors can achieve both nitrification and denitrification within the same treatment unit. One must still consider the effects of wastewater bypass on other waste constituents, such as influent pathogens that bypass around the aerobic layer.

4. Conclusions

The aerobic/anoxic DHS bioreactors consistently removed >80% COD, and oxidized >90% ammonia under continuous-flow operations using mixed-sponge densities and effluent recirculation. However, when 30% wastewater bypass was added to the design, effluent TN levels met the stringent Chinese discharge standard of 15 mg-N/L. Ammonia was slightly elevated in the 30% bypass reactor effluents, but this can be resolved using slightly lower bypass ratios to co-optimise TN and ammonia removal. Overall, results indicate DHS reactors with wastewater bypass are promising for decentralised wastewater treatment and should now be scaled up to assess their suitability for small community-scale applications.

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